COGGING TORQUE REDUCTION OF 6S-4P SPOKE-TYPE IPMSM USING A NEW COMBINATION OF ROTOR DESIGN

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This dissertation is dedicated to my beloved mother ROHAYAH BINTI ADNAN and my father BAHRIM BIN SALIM. My brothers, and sisters, who have always encouraged me with their love and prayers.

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ABSTRACT

Cogging torque is one of the vital issues in permanent magnet motors (PMM). Reducing cogging torque, which may cause vibration and acoustic noises, has become an increasingly critical issue in PMM. Low cogging torque significantly reduces acoustic noises and vibration, and enhances the positioning control of the motor for electric vehicle drive application. Therefore, this thesis exemplifies the significance of various rotor-PM configurations of three-phase 6S-4P Spoke-type (IPMSM). Initially, conventional cogging torque reduction techniques of skewing (Sk), notching (Not), radial pole pairing (Pop), and axial pole pairing (App) were analysed. Then, a new combination such as skewing with pole pairing (SkPop), skewing with pole axial pairing (SkApp), notching with pole pairing (NotPop), and notching with pole axial pairing (NotApp) were proposed and compared. The validity of the proposed designed techniques has been confirmed by 3-D Finite Element Analysis (FEA) executed in commercial JMAG designer version 14.1, under open circuit and short circuit conditions. Simulation results showed that the conventional techniques have reduced the cogging torque of 6S-4P Spoke-type IPMSM by 70.59%, 21.57%, 32.35%, and 48.04% for Sk, Not, Pop, and App respectively from the original value of 1.01Nm. The new proposed combination techniques reduce the cogging torque by 71.86%, 63.55%, 30.93%, and 51.55% for SkPop, SkApp, NotPop, and NotApp simultaneously. In addition, the cogging torque in 6S-4P Spoke-type IPMSM has been successfully reduced and the best technique is NotPop with 30.93% of cogging torque reduction, as well as the highest torque and power capabilities of 7.643 Nm and 959.03 W respectively. Finally, design analysis to improve NotPop performance has been done in this thesis. As a result, a new 6S4P Spoke-type IPMSM with low cogging torque and 19.05% torque improvement has been successfully designed.

ABSTRAK

Tork penuggalan adalah salah satu isu penting dalam motor Magnet kekal (PMM) dan mengurangkan tork penunggalan yang menyebabkan getaran dan bunyi akustik menjadi isu yang semakin penting dalam PMM. Tork penuggalan yang rendah dengan ketara mampu mengurangkan bunyi akustik, getaran, dan meningkatkan kawalan kedudukan motor untuk elektrik aplikasi pemanduan kenderaan. Oleh itu, tesis ini contoh kepentingan pelbagai pemutar-PM konfigurasi 3-fasa 6S-4P jenis jejari (IPMSM). Pada mulanya, teknik pengurangan tork penuggalan konvensional seperti Menyengetkan (Sk) dan mencatat (Not), jejari tiang berpasangan (Pop), dan paksi berpasangan tiang (App) dianalisis. Kemudian, gabungan baru seperti Menyengetkan dengan kutub berpasangan (SkPop), Menyengetkan dengan tiang paksi berpasangan (SkApp) dan mencatat dengan kutub berpasangan (Notpop) dan mencatat dengan kutub berpasangan paksi (NotApp) dicadangkan dan dibandingkan. Kesahihan teknik direka yang dicadangkan itu telah disahkan oleh 3-D Finite Element Analysis (FEA), dilaksanakan dalam komersial JMAG pereka versi 14.1, di bawah litar terbuka dan keadaan litar pintas. Keputusan simulasi menunjukkan bahawa teknik konvensional telah mengurangkan tork penuggalan untuk 6S-4P jenis jejari IPMSM oleh 70,59%, 21.57%, 32.35% dan 48.04% bagi Sk, Not, Pop, dan App masing-masing dari nilai asal 1.01Nm. Teknik gabungan baru yang dicadangkan mengurangkan tork penuggalan dengan 71,86%, 63,55%, 30,93%, dan 51.55% bagi SkPop, SkApp, NotPop dan NotApp serentak. Di samping itu, tork penuggalan dalam 6S-4P jenis jejari IPMSM telah berjaya mengurangkan dan teknik yang terbaik adalah NotPop dengan 30.93% pengurangan tork penuggalan serta ketumpatan tork dan kuasa keupayaan tertinggi masing-masing 7.643 Nm dan 959.03 W. Akhir sekali, analisis reka bentuk untuk meningkatkan prestasi NotPop telah dilakukan dalam tesis ini. Hasilnya, 6S4P jenis jejari IPMSM dengan tork penuggalan rendah dan 19.05% peningkatan ketumpatan tork telah berjaya direka.

TABLE OF CONTENTS

LIST OF SYMBOLS AND ABBREVIATIONS

ωN_m	-	Mechanical angular displacement
ϕ_m	-	PM flux linkage
ϕ_e	-	Field excitation flux linkage
θ	-	Angle of rotor position
θm	-	Rotor mechanical angle
α_a	-	Filling factor of armature coil
α_{cog}	-	Electrical angle of rotation
α_e	-	Filling factor of excitation coil
α_f	-	Filling factor
η	-	Efficiency
θ	-	Electrical angular position of rotor
ω_r	-	Rotational speed
ρ	-	Copper resistivity
A_n	-	Cross sectional area of PM
B_n	-	Magnetic flux density
f_e	-	Electrical frequency
f_m	-	Mechanical rotation frequency
H	-	Height of coil slot
I_a	-	Armature coil current
J_a	-	Armature current density
k	-	Harmonic order
kW	-	Kilowatt
ℓ	-	Stack length
L	-	Coil length
$L_{a,e}$	-	Stack length of machine
$L_{a\text{-}end}$	-	Estimated average length of armature end coil

L_d	-	d-axis inductance
$L_{a\text{-}end}$	-	Estimated average length of field excitation end coil
L_f	-	Total series inductance of field coil
L_q	-	q-axis inductance
N	-	Number of turns
n	-	Number of skewing steps
N_a	-	Number of turns of armature coil
N_c	-	Period of cogging torque
N_d	-	Neodymium
N_e	-	Number of cogging torque cycle
N_L	-	Least common multiple of slots
N_n	-	Number of notches
N_p	-	Number of periods of cogging torque
N_r	-	Number of rotor poles
N_s	-	Number of stator slots
p	-	Pole pairs number
Q	-	Number of stator slots
S_a	-	Armature coil slot area
T	-	End time
T_e	-	Electromagnetic torque
τ_{cog}	-	Cogging torque
T_L	-	Load torque
T_{max}	-	Maximum torque
V_1	-	Volume of coil slot
V_2	-	Volume of coil end
V_{total}	-	Total volume of coil
W_m	-	Energy in the air-gap
W_i	-	Stored magnetic energy
W_o	-	Average magnetic energy
$x_{d,q}$	-	Components in d-q axis
$x_{u,v,w}$	-	Components of U, V, and W phase
AC	-	Alternating current

AFFSPMM	-	Axial Field flux switching permanent magnet machine
BHmax	-	High energy product
Br	-	Retentively
DC	-	Direct current
EV	-	Electric vehicle
EMF	-	Electromotive Force
FE	-	Field excitation
FEA	-	Finite Element Analysis
FEFSM	-	Field excitation flux switching machine
FSM	-	Flux switching motor
HCF	-	Highest common factor
HE	-	Hybrid Excitation
HEFSM	-	Hybrid excitation flux switching machine
HEV	-	Hybrid Electric Vehicle
IPMSM	-	Interior permanent magnet synchronous motor
MMF	-	Magnetomotive force
NdFeB	-	Neodymium magnet
PM	-	Permanent magnet
PMSM	-	Permanent magnet synchronous machine
SPM	-	Surface permanent magnet

LIST OF TABLES

LIST OF FIGURES

LIST OF PUBLICATIONS

Journals:

(i) Fatihah Shafiqah Bahrim, E. Sulaiman, Laili Iwani Jusoh, M. Fairoz Omar, Rajesh Kumar "Cogging Torque reduction of IPM Motor using Skewing, Notching, Pole Pairing and Rotor Pole Axial Pairing." International Journal of Applied Engineering Research ISSN 0973-4562 vol.12, no.7, Mar 2017, pp. 1371-1376. (Scopus,Q3)

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Proceedings:

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LIST OF AWARDS

(i) **Bronze Medal** in Research and Innovation Festival, UTHM Malaysia, [R&I 2016]**:** Erwan Sulaiman, Mahyuzie Jenal, Fatihah Shafiqah Bahrim, Rajesh Kumar, Syed Muhammad Naufal Bin Syed Othman,"PMSM Electric Generator System for Micro turbine Application".

(ii) **Gold Medal** in Malaysia Technology Expo 2017 [MTE 2017]: Erwan Sulaiman, Fatihah Shafiqah Bahrim, Siti Khalidah, Laili Iwani Jusuh, Jaudah Abd. Rani, "D2 Motor for ECLIMO Electric Scooter".

(iii) **Gold Medal** in International Invention and Innovation Johor 2017 [IID2017]: Erwan Sulaiman, Mahyuzie Jenal, M. Fairoz Omar, Fatihah Shafiqah Bahrim, "Mobile Power Supply (MoPS)".

CHAPTER 1

INTRODUCTION

1.1 Research Background

In recent years, permanent magnet motors (PMMs) have gained significant attraction in electric vehicles (EVs) application. PMMs were accomplished with other motors in the market especially for the electric propulsion of EVs. In these EVs, the interior permanent magnet synchronous motors (IPMSMs) employed rare-earth permanent magnets (PMMs) as their main source of magnetic flux. In addition to that, the total weight and volume were considerably diminished for the specified output power [1]. Besides these advantages, the PMs also benefited from the increased power density, improved efficiency, and extraordinary reliability. Furthermore, the heat produced could be effectively dissipated to the surroundings. For these reasons, the PMs were accepted by leading automobile manufacturers such as Toyota, Honda, and M for their line of Hybrid Electric Vehicles (HEV). These motors show excellent reliability as they seldom need some kind of sliding contacts. Due to the reliability factor, these motors were also chosen for sensorless control drive applications. The HEVs generally require increased motor power density to support the speed and transmission of the vehicle. The most effective strategy to increase the motor power density has been to employ a combination of a high-speed machine along with a reduction gear [2]. Conversely, this combination resulted in some unfavourable results such as vibration, acoustic noise, large torque pulsation, excessive bus current ripple, and electromagnetic interference noise generation. This highlights the gap in the industry and hence research and development of permanent magnet synchronous motors (PMSM) have been gaining importance. The main motives of such PMSM studies are not only to reduce the material cost, but also to reduce the cogging torque effect as well as to improve motor performance by improving the quality of the motor [3].

1.2 Problem Statement

PMMs have been an inevitable part of the industry in general due to their high performances and effectiveness. There are several types of PMMs and each one of them is used for a specific purpose. Among the several types of PMMs, the interior-type PM (IPM) motor is the variety that has been generally employed for variable-speed drives [4]. The vital element for concern is the separation of permanent magnets (PM) caused by the centrifugal force at high speed. This separation could be avoided by inserting the PM inside the rotor core. By performing this insertion, it achieves high torque density, high efficiency, and their compactness. On the other hand, due to the unique structure of this interior-type PM motor, the interaction of the stator permanent magnets with the rotor teeth yielded a cogging torque, which was found to be relatively higher compared with other types of PM motors. Besides that, a serious distortion of air-gap flux density distribution resulted in copious harmonics in the back electromotive force (EMF) as well as high torque pulsations such as cogging torque and torque ripple [5]. Generally, high torque pulsations cause undesirable vibration, acoustic noise, poor position, pitiable speed control, performance degradation, and dangerous running failures [6]. Hence, it becomes necessary to lower the impact of high torque pulsations so as to minimise the ill effects arising due to it. Techniques to abate torque pulsations are very inadequate for spoke-type IPM motors. For the same reason, the techniques to minimise high torque pulsations has not been investigated thoroughly due to their rotor-PM configuration. Consequently, in order to address all these mentioned inadequacies, new techniques to minimise the torque pulsation becomes vital for the PMMs. For this, a 6S-4P Spoke-type interior permanent magnet (IPM) motor has been a subject of recent study and new techniques to minimise the torque pulsation including cogging torque has been proposed. The study also experiments with a rugged rotor structure suitable for assisted motor applied in EV.

1.3 Objectives

The main objective of this study is to minimise the cogging torque for 6S-4P Spoke-type IPMSM for assisted motor applied in EV. In achieving the main objective, there are some specific objectives that have to be fulfilled, which are:

1) To analyse the cogging torque characteristic of 6S-4P Spoke-type IPMSM using conventional rotor skewing (Sk), rotor pole pairing (Pop), rotor notching (Not), and rotor pole axial pairing (App) methods for cogging torque reduction.
2) To design and analyse a new combination of skewing with pole pairing (SkPop), skewing with pole axial pairing (SkApp), notching with radial pole pairing (NotPop), and notching with axial pole pairing (NotApp) for cogging torque reduction.
3) To design and analyse performance of the best cogging torque reduction method for 6S-4P Spoke-type Interior Permanent Magnet Synchronous Motor (IPMSM) for performance improvement.

1.4 Scope

The scope limitation of this research is parallel with the objectives.

1) This project is to design three-phase 6S-4P Spoke-type IPMSM for assisted motor applied in EV.
2) Various conventional and proposed cogging torque minimisation techniques are used and compared using 3D-FEA solver by JMAG Designer ver 14.1, released by Japan Research Institute (JRI). Analysis result of motor characteristic based on open circuit and closed circuit analysis.
3) All the proposed design parameters, restrictions, and target specifications of the three-phase 6S-4P Spoke-type IPMSM are listed in Table 1.1. The limit of the current density is set to the maximum 30 A_{rms}/mm^2 for the armature winding.

Table 1.1: Parameters of 6**S**-4P Spoke-type IPMSM.

Parameters	**Unit**	**6S-4P Spoke-type IPMSM**
Stator outer radius	mm	44.0
Stator inner radius	mm	26.0
Motor stack length	mm	54.0
Shaft radius	mm	13.5
Outer Radius of rotor (mm)	mm	25.5
Permanent magnet width (mm)	mm	4.2
Air-gap length	mm	0.5
PM weight	kg	0.83
Speed	rpm	4800

1.5 Thesis Outline

This thesis consists of five chapters and the summary of each chapter is as follows:

a) Introduction

The beginning chapter of this thesis gives some introduction regarding the research including the background of IPSM, problem of existing motors employing cogging torque effect, research objectives, and research scope.

b) Literature Review

The second chapter is a literature review that summarises the basic theory of torque pulsation and cogging torque phenomenon in electrical machines. Various cogging torque minimisation techniques from previous research are discussed in detail and compared.

c) Research Methodology

This chapter describes the inventive steps of existing and proposed cogging torque reduction techniques implemented using JMAG-Designer software version 14.1. The project implementation is divided into three steps including design and analysis of existing cogging torque reduction method, design and analysis of new combination method for cogging torque reduction, and finally design improvement of the best cogging torque combination technique. The three steps are divided into two parts, which are geometry editor and JMAG-Designer. The geometry editor is for designing and JMAG-Designer is for

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